A comparative study of two conductive inkjet inks for fabrication of RF circuit structures

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Abstract

Two commercially available silver inks were inkjet printed to fabricate the seed tracks (seed layers) of radio frequency (RF) circuit structures on a high frequency substrate material. One of them is a nanoparticle based ink, and the other, a non-particle based organic silver complex ink. Subsequent to printing, these seed layers were copper plated using an electroless copper plating process, to impart the desired thickness to the circuit structures. The inkjet printing-electroless plating process combination was validated with the example of an S-band filter and an RF transmission line. Prior to the fabrication of the circuit structures, the substrates were plasma treated, in order to modify their surface and promote mechanical interlocking with the printed structures. Finally, experiments were conducted to determine the solderability of inkjet printed as well as printed-plated structures. Conclusions on the suitability of the two inks for RF circuit fabrication have been drawn based on experimental results.

1. Introduction

Inkjet printing, a maskless rapid manufacturing technique, combines flexibility with low-cost. In the context of printed electronics, this technique has an increasingly prominent role, and the future may see inkjet proliferate into mass production of electronics [1]. To facilitate inkjet printing's rise to prominence in electronics fabrication, many types of inks have been developed. The process of ink development is an on-going one, with various manufacturers around the world striving to strike the right balance between electrical performance, printability and interaction of the ink with the environment. Nanoparticle-based inks and organo-metallic complex inks are two main types of ink formulations that are available for inkjet printing of conducting structures. Details concerning the jetting of these ink types on different substrate materials have been widely published [2 - 5].

During the course of this research, radio frequency circuit structures in the form of an S-band filter and a transmission line were fabricated using inkjet printing and electroless plating. Two commercially available silver inks were selected to print the seed tracks, onto which copper was electroless plated. The main reasons to include electroless plating in the process chain is to overcome the relatively lower electrical conductivity of inkjet printed structures due to pores, cracks, surfactants and other imperfections [6, 7], as well as to avoid dimensional inaccuracy and other associated problems that accompany inkjet printing of multiple stacked tracks. Such an approach for RF applications has already been discussed by Mantysalo et al [7].

Qualitative scotch tape adhesion tests, performed on inkjet printed test structures, showed that inkjet printed tracks exhibit poor adhesion to the substrate, the latter being a polymer. In general, polymers show a low propensity towards chemical bond formation due to their quasi-inert surface. As a result, surface modification techniques are frequently applied to polymers before metal deposition, to create a strong interface [8 - 10]. Prior experience showed that when subjected to electroless plating, inkjet printed tracks on a relatively smooth, untreated substrate de-bonded, primarily due to the weak bonding forces. To prevent this de-bonding, the substrates were plasma treated prior to inkjet printing, so that the tracks adhere better to them. An account of this pre-processing step as well as RF circuit structure fabrication and post-fabrication RF measurements is provided in this paper, along with a comparative analysis of the suitability of the two ink types used.

2. Approach, materials and methods

A band-pass S-band filter and a transmission line were designed using the software program Advanced Design System (ADS from Agilent Technologies, USA). RO4000 series substrates (Rogers Corporation, USA) were subjected to tetrafluoromethane/oxygen plasma to increase the surface energy and to impart surface roughness. The plasma treatment was carried out in a barrel type plasma reactor (TePla 3067 from Technics Plasma GmbH, Germany). The seed tracks for the RF structures under discussion were inkjet printed using a piezoelectric drop-on-demand inkjet printer (Jetlab-4 from MicroFab Technologies, USA). A nozzle with 60 μm inner diameter was used for this purpose. As mentioned before, two different inks were used to print the seed tracks on different substrates. One of them was a silver nanoparticle-based ink, with 60% metal content by weight, and the other, an organic silver complex compound, with 15% metal content by weight. Specific information about the inks as well as their producers has been consciously left out. Copper plating of the printed tracks was carried out using a commercially available electroless copper system (Envision-2130 from Enthone Inc., USA). The RF performance of the fabricated structures was evaluated with an HP 8150 Network Analyzer. Experiments to determine the solderability of the printed and printed-plated tracks were done at various soldering temperatures. A JSM-6400 scanning electron microscope (SEM) (from JEOL Limited, Japan) was used for microstructure analyses.

3. Experimental part

3.1. Filter and transmission line design

The design of the filter as well as the transmission line is depicted in figure 1(A). The S-band filter is at the top and the 50 ohm reference transmission line is at the bottom. Figure 1(B) shows the cross-section of the test design. The functional elements of the stripline filter were realised by sections of high-impedance/low-impedance lines: high-impedance (narrow) lines substituting inductive elements and low impedance (broad) lines substituting a capacitive element. The dielectric constant of the substrate material is 3.55 and its dielectric loss tangent is 0.0027. The design thickness of the circuit structures in this design is 17.5 μm. For fabrication reasons, the thickness of the dielectric medium consisted of four substrate layers, each 0.5 mm thick. The substrate layer containing the RF structures is, as shown in figure 1(B), sandwiched between one layer on one side and two layers on the other. Copper cladding on the topmost and the bottommost layers are the ground planes. The 50 ohm transmission line was included in the design with the aim of locating the problem source, should the filter not yield the desired results; i.e. to identify whether the eventual discrepancy was due to the printed-plated filter or the printing-plating process itself.

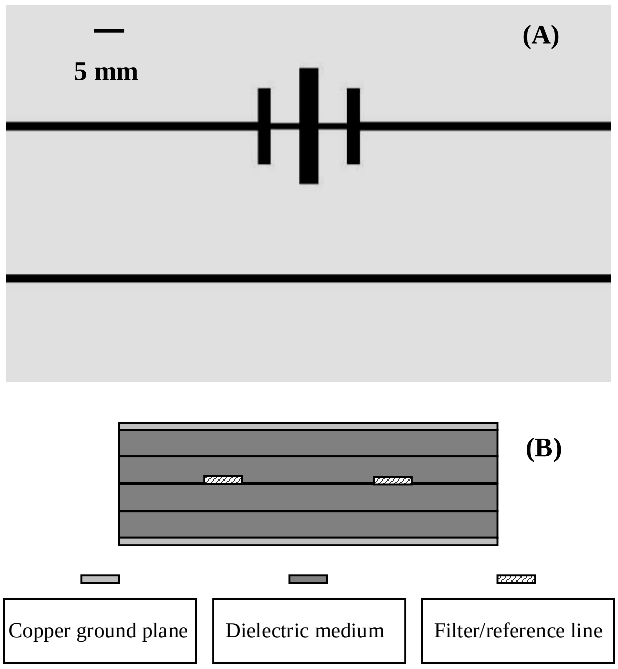

Figure 1: (A) Filter and transmission line design; (B) Cross-section of the design.

3.2. Plasma treatment

Scotch tape tests done on test structures inkjet printed on RO 4000 series laminates indicated that the adhesion between them was poor. Figure 2 shows a standard scotch tape peeled off a test structure. It is clear from this figure that the peel off was almost complete, an indicator of poor adhesion. It was decided to plasma treat the substrates, to improve adhesion by increasing the surface energy, and more importantly, by roughening the surface of the substrate thereby promoting mechanical interlocking. The 'anchoring spots' in a rough substrate promote interlocking and hence the adhesion. In metal-polymer systems, this mechanism is the most important factor in determining the adhesion strength of an interface [11, 12]. However, the adhesion provided by chemical bonding cannot be neglected. By systematically varying the parameters of the plasma treatment, the substrates were made rough enough, but not too rough so as to preclude accurate ink deposition. A substrate that is very rough or that has surface pores will have a deleterious effect on RF performance of the printed structures. The details of the plasma treatment have been furnished in a separate publication [13]. Micrographs of a RO4000 series laminate before and after plasma treatment is shown in figure 3.

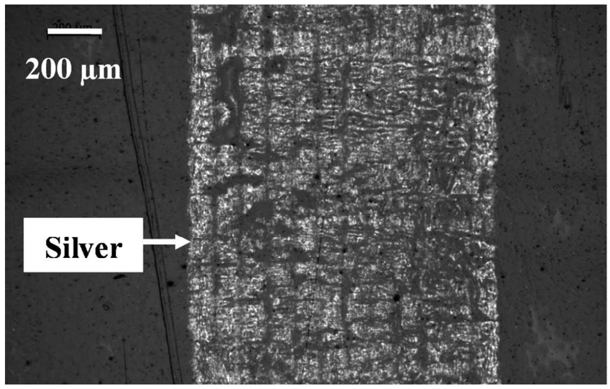

Figure 2: Scotch tape peeled off from a test structure inkjet printed on an untreated RO4000 series laminate.

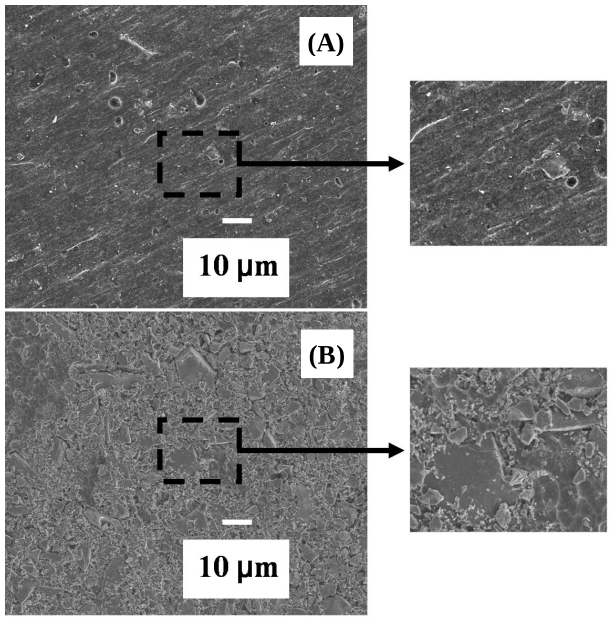

Figure 3: RO4000 laminate that is (A) untreated and (B) plasma treated.

3.3. Inkjet printing - electroless plating

Inkjet printing of the seed tracks for the RF structures, using the nanoparticle ink, was carried out with the substrate holder pre-heated and maintained at 100°C. The high substrate temperature ensured flash evaporation of the droplets upon landing, to control the behaviour of the ink on the substrate. Moreover, quick evaporation of the solvent tends to minimise the so-called 'coffee-stain' or 'coffee-ring' effect. As far as the organic silver complex ink is concerned, the substrate holder was maintained at 50°C; this temperature was sufficient to achieve the desired droplet behaviour on the substrate.

In both cases, only one layer of seed tracks was printed, as that was sufficient to induce the growth of copper during the subsequent plating step. The optimal droplet spacing was found to be 0.1 mm in both X and Y directions. The width of a single printed track was about 150 µm. The number of tracks printed side-by-side depended on the length or width of individual sections. It is to be noted that since the designed lengths or widths of the individual sections of the filter were not exact multiples of a single track width, there were minor deviations from the design dimensions. After printing, the RF structures were sintered to impart continuity. The structures printed using the nanoparticle ink were sintered at 210°C for 60 minutes, while those printed using the organic silver complex ink were sintered at 150°C for 30 minutes.

Subsequent to sintering, the substrates containing the seed tracks were cleaned in a neutral aqueous cleaning solution for five minutes at room temperature, followed by a rinse in de-ionised water for one minute. Then they were electroless plated in a plating bath that was maintained at 48°C. The combined thickness of the printed-plated RF structures was approximately 3.5 µm. Even though the design thickness of the structures was 17.5 µm, this thickness was deemed sufficient due the tendency of electromagnetic waves to travel along the skin of a conductor at high frequencies. This phenomenon is known as the 'skin effect'. The skin depth is frequency dependant and can be calculated using the formula given below [14]:

$$d = \sqrt{\frac{1}{pfms}} ,$$

where δ is the skin depth, f, the frequency of the incident electromagnetic wave, μ, the permeability constant and σ, the electrical conductivity of the conductor. Using this formula, the maximum skin depth required for the S-band range (2 to 4 GHz) was calculated as 1.45 µm. To compensate for the lower conductivity values of inkjetted silver-electroless copper combination in comparison with bulk copper and bulk silver, the final RF structures were fabricated to be about 3.5 µm thick, as mentioned above. Figure 4 shows a fabricated RF filter and transmission line.

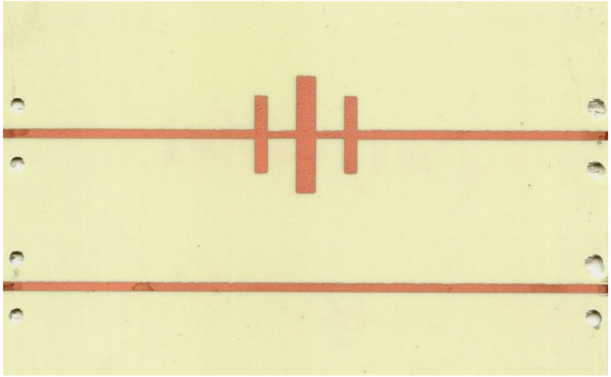

Figure 4: An inkjet printed-electroless plated S-band filter and transmission line on RO4000 series substrate.

3.4. RF characterisation

The fabricated RF filters and transmission lines were subjected to network analysis, to determine their performance characteristics. The additional substrate layers, two of them with copper ground planes, were included in the RF test specimen, as discussed in section 3.1. Prior to the analysis, sub-miniature version A (SMA) connectors were mounted on them. To eliminate the air gap between the dielectric substrates or between the RF structures and the adjacent substrate, the test specimen was clamped between two aluminium plates. During the analyses, the frequency of the incident waveform was increased from 1 GHz to 10 GHz in steps of 45 MHz.

4. Results and discussion

4.1. Network analysis

From the network analysis, the insertion loss (*S21*) and the return loss (*S11*) of the filters and transmission lines were obtained. Insertion loss is a measure of energy lost during the transmission of a signal through the filter. Return loss accounts for the signal reflection due to, for example, impedance mismatch. The graphs representing the response of the filters are shown in figures 5 and 6, the former depicting the return loss and the latter, the insertion loss.

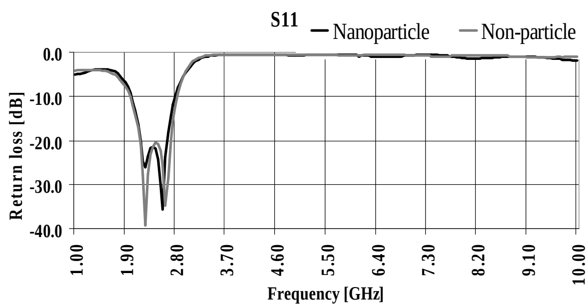

Figure 5: Comparison of the return losses of the S-band filters.

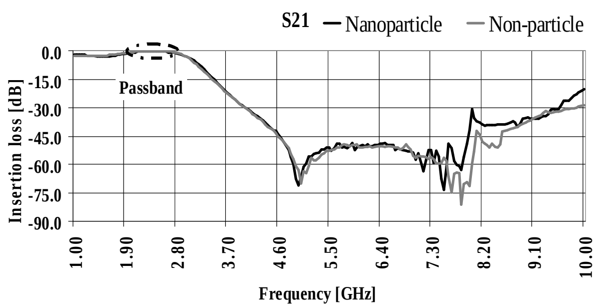

Figure 6: Comparison of the insertion losses of the S-band filters.

From these figures, it is evident that in the passband, the *S* parameters of the two filter types are in mutual agreement, *S21* more so than *S11*. The values in the passband for the former are almost identical, with insertion losses close to 0 dB. The *S11* curve for the filter with non-particle silver seed layer is steeper with lower losses than the other filter, in the passband. However, this variation cannot entirely be attributed to the electrical properties of the inks; the printing parameters for the two ink types were different, resulting in slightly varying seed track dimensions. Moreover, as mentioned in section 3.3, deviations from design dimensions can also be cited as a reason for the variation in the response of the filters.

The performance of the transmission lines is presented in figures 7 and 8.

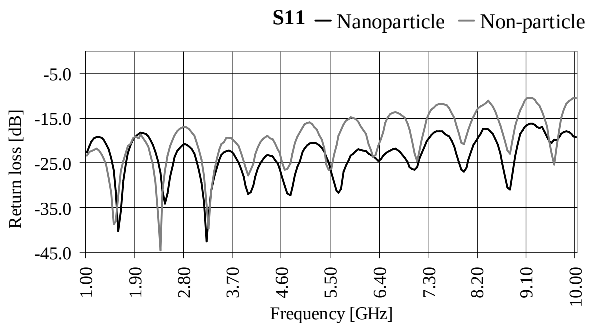

Figure 7: Comparison of return losses of the transmission lines.

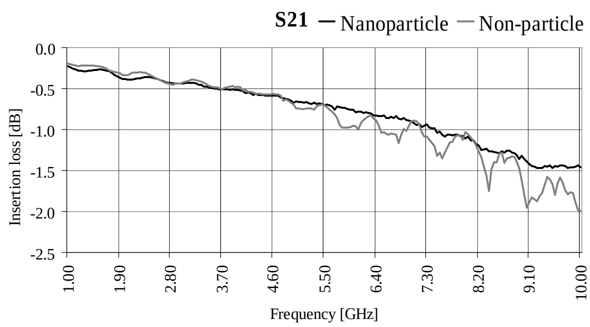

Figure 8: Comparison of insertion losses of the transmission lines.

The return losses for the two transmission lines agree fairly well with each other, as shown in figure 7. This figure also highlights a wave-like response of the two transmission lines. This is due to the fact that the network analyser was connected using coaxial cables to the coaxial SMA connectors, which were, in turn, mounted on the striplines. Calibration of the network analyzer was done up to, but not including, the SMA connectors. This transition from coaxial to stripline at the input, and stripline to coaxial at the output, is considered the reason for the periodic distortion in the responses of the transmission lines.

Figure 8 shows the better performance of the nanoparticle-based transmission line, at frequencies greater than 5 GHz. The reason for this is the unevenness of the surface of the transmission line with non-particle-based seed layer, which was more pronounced than the other transmission line. At higher frequencies, where the skin effect plays a major role in determining the transmission characteristics, the pronounced surface undulations of the filter resulted in a slightly inferior performance.

4.2. Comparison of the inks

It was found that both the inks are susceptible to adhesion problems during electroless plating. These problems encountered during initial plating trials were overcome by plasma treatment. A direct one-to-one comparison of the two inks cannot be justified, as their formulations are different. However, in the context of inkjet printing of electronic circuits, certain conclusions can be drawn with respect to their suitability. Since both the inks have good electrical properties besides being easy to print, perhaps the most important issue is the sintering temperature. The glass transition temperatures (Tg) of a number of materials used as printed circuit board (PCB) substrates are lower than 200°C, some even lower than 150°C. Exceeding this temperature will have a negative impact on the properties of the material. So, to incorporate inkjet printing and hence sintering into the PCB manufacturing chain, substrates like the one used in this research (RO4000 series), with a Tg well above 200°C, should be selected. This would require a change in many existing applications, where substrates with low Tg values are used. A more practical solution will be to formulate conducting inks that can be sintered at 100°C or lower. As things stand, the organic silver complex ink is applicable for a wider range of substrate materials than the nanoparticle ink, due to its lower sintering temperature and time.

Solderability is another important issue that needs attention, as soldering is an integral step in circuit fabrication. Experiments were done with solder temperatures ranging from 200°C to 300°C, to determine the solderability of the tracks printed using the two ink types. As depicted in figure 9, both the tracks were not able to withstand the process conditions - the solder seemed to dissolve silver. On the other hand, the copper plated silver tracks exhibited good solderability even at 300°C, as shown in figure 10. The poor solderability of inkjet printed silver poses a problem that cannot be ignored, as plating does not always accompany inkjet printing. It would be interesting to see how the ink manufacturers address this problem.

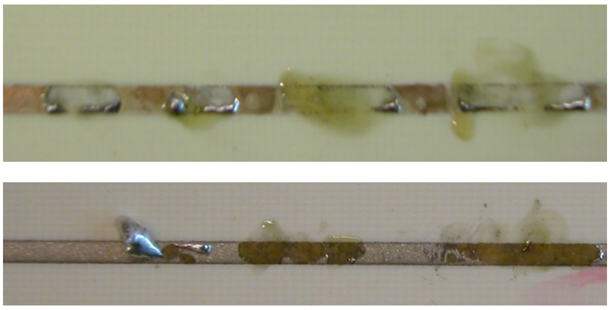

Figure 9: Soldering trials carried out on tracks printed using the nanoparticle-based ink (top) and non-particle-based ink (bottom).

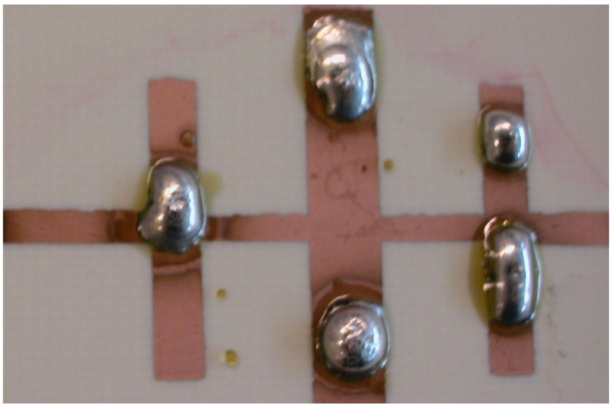

Figure 10: Soldering on inkjet printed-electroless plated tracks.

5. Conclusions and outlook

The foremost conclusion of this study is that the combination of inkjet printing and electroless plating was found to be suitable for RF circuit fabrication. The network analyses of circuits fabricated for application in the S-band range showed that this method is indeed suitable for high frequency applications.

The receptiveness of the two ink types to plating was good. However, a comparison of plating rates and detailed microstructure analysis of the plated layers were not done. They would shed more light on the ink characteristics.

Some of the shortcomings of inkjet inks were highlighted by the poor solderability as well as relatively high sintering temperatures of the inks. The poor solderability of inkjet printed silver was overcome in this case by the plating process. As far as the sintering temperature is concerned, development of inks that can be sintered at temperatures lower than 100°C will go a long way in promoting the widespread use of inkjet printing in electronics applications.

Future work will aim at (a) furthering the know-how on the suitability of inkjet printing-electroless plating for RF applications beyond the S-band range, and (b) determining the adhesion strength of the inkjet printed structure-substrate interface, by a qualitative test method like pull-off test or modified peel test.

6. Acknowledgements

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